FINAL VERSION FOR WORKSHOP, IGS
PRINTED MARCH 11, 1997

# IGS Position Paper: Site Specific Effects

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# Introduction

During the last few years, an increasing number of permanent GPS sites have been established. The global IGS networks of continuously operating GPS receivers formed with these sites are used for precise orbit determination, global geodesy and geodynamics, and atmospheric reasearch. The use of permanent local and regional networks, with maximum baseline lengths of ~50 km and ~1500 km, respectively, has also increased. The most demanding task for these, often multipurpose, networks is to monitor three-dimensional crustal motions associated with regional geophysical phenomena, such as regional plate tectonics [e.g., *Blewitt et* al., 1993; *Bock et al.*, 1993; *Dragert and Hyndman, 1995; Tsuji et al., 1995]* or postglacial rebound [e.g., *BIFROST project members, 1996].* The demonstrated repeatability of horizontal position estimates for these regional networks is currently of the order of 1–2 mm and typically a factor of 3--5 greater for the vertical baseline component. Through the IGS pilot project on densification and extenstion of the IERS Terrestrial Reference Frame several of these local stations are now used by the IGS.

There are many advantages to continuously operating GPS networks. Stable pillars with fixed antennas eliminate errors associated with variations in the measurement of the local vector from the reference marker to the phase reference point of the antenna. For fixed pillars in a continuously operating network, the reference marker is usually a fixed, well-defined point on the antenna. In addition, denser position estimates (spatially and temporally) decrease the statistical uncertainty of the results. Continuously operating networks may also serve as a global or regional reference frame for different types of regional and local surveys. Another essential advantage, related to the subject of this position paper, is the increased ability to study and eliminate unmodeled systematic effects on daily estimates of site positions, both short- and long-term effects,

The improvement in precision obtained from GPS observations over recent years has revealed problems related to the local conditions at the GPS sites. In order to further improve high precision GPS positioning, orbit determination, and estimation of atmospheric parameters, investigations of site dependent effects are required. For example, concerns have been raised regarding the monuments used and the long- and short-term mechanical and electromagnetic stability of the sites. One of the more severe effects is the apparent variation of the GPS antenna phase center as a function of the elevation angle of the observed satellite. This effect could be refered to as a combined effect of the receiver, antenna. radome. and the signal.

Another source of error which currently is receiving much attention in the community is apparent random motions of the geodetic monument. These motions have been found by some researchers to be random-walk-like [e.g. Johnson *and Agnew, 1995]* while other time series show no evidence for random walk behavior. This effect may well be associated with the type of monument used and the site locations. These investigations will have to continue and are most effectively addressed using continuous GPS measurements gathering data in a large variety of monuments and geological settings.

Curently available IGS products include predicted, rapid, and precise orbits (with approximate accuracies of 50 cm, 10 cm, and 5 cm, respectively) with consistent Earth orientation files, station time series for densification of the IERS Terrestrial Reference Frame (ITRF), the Ionospheric Total Electron Content (TEC), and the tropospheric Precipitable Water Vapor (PWV). It is important to note that site-specific errors cannot be separated out when data from the global IGS sites are being used to determine orbits and reference frame. To be able to constrain the common mode of motion, sometimes in the submillimeter range, in a regional or local network a strong reference network is needed. The origin of the reference frame must be maintained with a high degree of robustness. In addition, orbits must be compatible with the reference frame. For this purpose data from the IGS network needs to be regularly examined in detail,

This position paper adresses the problem of site-specific errors and present some recommendations on how to handle these sources of error.

# Site Specific Errors

We have chosen to divide the site specific error sources into 3 subgroups. The first group consists of problems associated with the receiver, antenna, radome, and the signal. These are effects that will not, in general, change on a day-to-day basis. However, they might introduce biases in the solution. .-is long as nothing changes the effect stays the same. If something changes, such as the satellite constellation (e.g., introduction of GLONASS) or the elevation cut-off angle, the results/products will be affected. The influence is especially obvious looking at the PWV and the estimates of the vertical components where bias terms can be introduced [ e.g. *Elósegui et* al., 1994; *Niell et al.,* 1994; *Niell*, 1996; *Carlsson et al.*, 1997] (see also Figure 1). Such a bias could seriously affect the interpretation of the GPS data. From Baltex/Gewex (the Baltic Sea Experiment) [*Elgered et al., 1997]* in the World Climate Research Programme (WCRP) and Global Energy and Water Cycle Experiment (G EWEX) we note that the bias term in the estimates of PWV from GPS data should be ≲1 mm in PWV (or equivalently about ≲6 mm in zenith wet delay) to be useful.

The second group represents areas of site effects that will vary, but will only periodically affect the IGS products. Precipitation, multipath, atmospheric pressure loading, and atmospheric gradients are probably the most important of these, but others may be discovered.

Finally, the third group consists of errors that might affect the long-term stability of a site such as the location of the site, ground, and the monument. Most of the material related to this specific group of site errors are rather new. These errors may seri*ously* affect the reference frame and the geodynamical projects. Most of the time series from permanent GPS networks are yet too short to make any definite conclusion. Many of the longest GPS time series existing today are found in the IGS global network, and many of them have not yet been carefully examined. Techniques which can be applied to data from individual sites [e.g. *Zumberge et al., 1997]* should be valuable in assesing the site-specific nature of the errors from all groups.

## GPS Antennas

It has been found that antenna-to-antenna phase differences can introduce range biases at the several centimeter level, which may limit the precision of the measurements [*Rocken*, 1992]. Differential phase errors due to GPS antennas will not only affect the precision in GPS networks with different types of antennas, but also in networks using identical antennas if the network covers a large spatial area (baseline lengths ≳1000 km) [*Schupler and Clark*, 1991; *Schupler et al.*, 1994]. Differential phase errors in regional networks (baseline lengths ≲1000 km) using identical antennas are dependent on the electromagnetic environment around each individual antenna.

The problem of antenna mixing was addressed at the IGS Analysis Center Workshop in Silver Spring, 1996. Two sets of phase calibration corrections (PCC) tables have been put together based on material presented by *Mader and MacKay [1996], Rothacher and Schär [1996]*, and *Meertens* et al. [1996a] to be used by the IGS Analysis Centers and others in the GPS community: (1) a set of "mean" phase center offsets and (2) a set of elevation-dependent PCC and offsets relative to the Dome Margolin T antenna.

Since the PCC values are all relative to the Dome Margolin T antenna some effects of antenna mixing still remain. Even with the same type of antenna the variation in the apparent phase center as a function of elevation angle will influence the results on longer baselines. Therefore the task of getting absolute calibration of the antennas through, e.g., chamber measurements or antenna simulation software may be essential for some applications even though these calibration values most likely will change when the antenna is deployed in the field.

Effects like these can of course be reduced by utilizing antennas less sensitive to scattering from external structures. One way to achieve this is to reduce the side- and back-lobe levels of the amplitude patterns by means of well designed ground-planes. For this purpose new antenna designs have been proposed [see e.g., *Alber*, 1996; *Ware et al.,* 1997; *Jaldehag*, *1995;* and *Clark et* al., 1996]. Furthermore, several groups are currently developing methods to perform absolute field calibration of antennas [see e.g., *Wübbena et al.*, 1996] and insitu calibration of antenna/pillar systems.

Suggestion: *The establishment of precise absolute calibrations of GPS antennas by means of chamber measurements and antenna pattern calculations is essential.*

## Antenna-Pillar System and the Signal

Here we concentrate on the site-dependent error associated with the electromagnetic coupling between the antenna and its nearby environment [e. g., *Tranquilla*, *1986; Tranquilly and Colpitts*, *1988].* The total electromagnetic field of an antenna which radiates a signal in the presence of conducting structures may be expressed as a superposition of the transmitted field and the fields scattered (i.e., reflected and diffracted) by the structures. By reciprocity, the same is true for a receiving antenna. The significance of the scattered field depends on the degree of electromagnetic coupling between the antenna and the scatterer, that is, the distance to the scatterer and the size and reflectivity of the scatterer. Signal scattering affects both the amplitude and phase of the received GPS signal, presumably independently at each site in a network. This independence creates differential phase errors.

Scattering from structures in the vicinity of the antenna effectively changes the antenna phase pattern, and, thus, affects the precision of the carrier phase measurements of the GPS signal. In studies by *Elósegui et al. [1995]* and *Jaldehag et al.* [1996a] it was shown that estimates of the vertical component of baselines formed between sites using identical antennas were dependent on the minimum elevation angle of the data processed. Both studies found that the elevation-angle- dependent systematic effect was associated with non-identical pillar arrangements, causing differential phase errors due to scattering from structures associated with the mounting of the antenna to the pillar, and with the pillar itself. Even the most perfectly calibrated antenna the antenna phase pattern will change when attached to a pillar. All pillars have an effect.

*Jaldehag et al.* [1996a] demonstrate that estimates of the vertical component of many baselines strongly depend on the minimum elevation angle (elevation cutoff angle) of the data analyzed. Offsets of several cm in the vertical component of the Onsala IGS station were evident when the elevation cutoff angle was changed from 10° to 20° (see Figure 2). A significant part was found to be due to differential phase errors caused by scattering from structures associated with the mounting of the antenna to the pillar and with the pillar itself. The horizontal components of baseline are less affected. The offets in the horizontal components were found to increase with baseline length. For the longest baselines (~1500 km) offsets of more than 5 mm are evident in the north component when the elevation cutoff angle is changed from 10° to 20°. These offsets are most likely due to differential phase errors caused by nonuniform antenna phase pattern, an effect that presumably increases with baseline length and which also might increase because of scattering from the pillars and the antenna mounts.

*Implication for the IGS*

The effects identified by several groups are due to baselines formed between sites using different types of pillars and antenna mounts. Similar effects are probably also present for sites in the global network. All users of data from these sites will thus be affected to a level which is not very well documented. As the precision and accuracy of GPS measurements improve in general, antenna phase pattern variations due to different pillars and antenna mounts could be the major error source in just a few years, if not now.

Suggestions: *Modeling of the scattering effect, or rather the complete phase response of the antenna system, including the pillar, is an* important issue *for future Improvements of the GPS technique. One possibility to minimize these problems in the future would be to introduce specific recommendation on antenna/pillar system for new sites being established in the scientific GPS community. This system should, of course, be well- documented and phase-calibrated.*

*The problem in the existing IGS network is that* unlike *many of the* local and *regioal networks the antenna-pillar systems are quite different from station to station. The recommendation for those sites is that they should be carefully examined and calibrated. One* alternative *might be to draw up procedures for- looking at the* time series, *behavior in elevation cut-off tests and the repeatabilit y (day- to day) of multipath.*

Radomes - Protective Covers

At several permanent GPS sites located in areas with periodically severe environmental conditions (snow, rain) radomes have been employed. Many of the Global IGS sites do have a radome covering the antenna, even more are expected to follow after the extention and densification scheme of the IGS to use regional GPS networks. Some of these regional networks are located at higher latitudes and radomes have been used to protect the antenna from snow accumulation. Until recently, most radomes in use have had a conical shape e.g. in order for the snow to slide off.

It is important to note that all materials have some effect on a electromagnetic wave. Radomes appears to delay and refract the GPS-signal in a similar way as snow [*Jaldehag et al.,* 1996 b]. Several groups have recently been investigating effects due to the excess signal path delay through the radome. Different radomes have been tested in an anechoic chambers [*Clark et al.,* 1996: *Meertens et al.,* 1996b] as well as in field tests [*Meertens et al.,* 1996b: *Jaldehag et al.,* 1996c]. All tests show that a conical cover may cause cm-level vertical errors when the tropospheric delay parameter is estimated. Preliminary results of hemispheric radomes shows a smaller, 2 mm vertical offset. Similar tests have been carried out within the Swedish Permanent GPS network, Figure 3 shows an elavation angle cut-off test using a four station network in Sweden. Two stations were equipped with hemispheric radomes while the other stations used different types of cone-shaped covers. A clear elevation dependent effect is seen for the cone-shaped radomes while the the two sites with hemisperic radomes show much less systematic behavior.

We can conclude that all radomes effect the GPS signal at some level and appears as an excess signal path delay which will map into other parameters in the GPS software. The effect of the protective covers can most likely be misinterpreted as a tropospheric effect in a similar way as snow. The effect is more or less constant and may be calibrated or modeled. The recently employed hemispheric seems to show much less elevation dependence. The influence on the tropospheric wet delay estimates and subsequently, the vertical component will only be on the 1-2 mm level. We also assume that differential effects due to the excess signal path delay through the radome are canceled out as identical radomes are employed in local or regional type of network but this may not be enough in large-area networks.

### *Implications* for *the IGS*

The majority of IGS stations do not have a radome, although some sites within the core and global network have conical radomes. For climate studies and weather forecasts the bias of the GPS estimates of zenith wet delay (ZWD) has to be about 6 mm or less or equivalently less than 1 mm in the PWV content. The effects of those stations presently equipped with protective covers is dependent on the type radome used and the elevation cut-off used by the IGS Analysis Centers. Any changes at the station like addition/removal/change of radome will affect the time series for that site and possibly also others through the orbit determination.

Suggestions: *The effects of radomes must be carefully investigated , including these effects on sites of IGS network. Recommendations for radome use should be developed. The changing of radomes should be carefully logged.*

## Precipitation

Signal propagation delay during snow storms has been investigated by, e.g., *Tranquilly and Al-Rizzo [1993]* and *Tranquilly and Al-Rizzo* [1994] who demonstrated that due to the localized nature of many snow storms differential effects may cause systematic variations at the centimeter level in estimates of the vertical coordinate of site position. Systematic variations introduced by snow storms may, however, if short-lived (minutes co hours), be reduced to a high degree by data averaging, A potentially more serious effect of heavy snow precipitation is the accumulation of snow on the top of the GPS antenna and On its surroundings, such as on the top of the GPS pillar or, when present, on the radome covering the antenna. This accumulation may last for days, weeks, or months. *Webb et al. [1995]* reported variations on the order of 0.4 m in estimates of the vertical coordinate of site position. The variations were correlated with the accumulation of snow over the antenna. Variations at the several centimeter level in estimates of the vertical coordinate of site position strongly correlated with changes in the accumulation of snow on top of GPS antennas have also been observed by others [*Jaldehag* et *al.*, 1996b; *BIFROST project members, 1996; Meertens et al.*, 1996a]. The results indicate that the variations in the vertical coordinate of site position can be fully explained by reasonable accumulations of snow which retard the GPS signals and enhance signal scattering effects.

Suggestions: *The effect of snow accumulation on the antenna/pillar system can introduce errors at the several cm-level. Methods to detect and model such errors need to be developed. Another option is* of *course to design antenna/pillar systems on which snow accumulation are less likely to take place.*

## Horizontal Atmospheric Gradients and Air Pressure Loading Effects

Local atmospheric effects could be a significant source of error. Like several other types of errors, elevation-dependent.

In the data processing the atmosphere is normally considered to be spherically stratified. We assume that one equivalent ZWD value determines the wet delay in any direction, given a certain elevation angle. More advanced models, using more parameters to describe the atmosphere, have been proposed as alternatives to this very simplified model [e.g., *Davis et al.*, 1993]. Studies have also been carried out to solve for such parameters in the Very-Long-Baseline Interferometry (VLBI) technique [*MacMillan, 1995].* Using the model presented by *Davis et al. [1993]* one can decompose the ZWD into one azimuth independent term, and two gradient components. Figure 4 shows the east-west gradients at Onsala, with the formal one-sigma error bars, estimated from WVR data. From Figure 4 we can see that the sizes of the gradients are typically less than 2 mm, but periods exist

.-where they can reach up to 1 cm as, e.g., the 15th of August. Such gradients we expect can result in errors of the order *of* several mm in the final PWV estimate. Several groups are now implementing possibilities to estimate horizontal gradients in the software *[Bar- Sever and Kroger*, 1996; *Chen and Herring,* 1996].

The lack of pressure data available during the GPS analysis can be the reason for different errors. During the entire GPS processing we have to model variety of external and internal influences on the crust of the earth. One effect currently not normally modeled is the pressure loading. The vertical position of the GPS receiver changes due to different atmospheric pressure loading the Earth more or less *[vanDam and Herring, 94]*. Extreme values could effect the vertical component of the GPS estimates on the cm level. These effects are of course related more to the general presssure field in the region rather than to a specific site. To properly model this effect a grid of pressure data has to be available.

Suggestions: *These effects could be significant at the mm-level or greater. Unfortunately, it* is very *difficult to isolate these effects from other elevation-angle-dependent effects (multipath, scattering, snow/ice, etc.). Small variations* in *the vertical component are also caused by these other errors. We are thus not in the position of being able to correct for horizontal atmospheric gradients and loading errors optimally. A t this point, theoretical studies are needed to quantify these effects, and to understand how we can best deal with these problems.*

## Local Stability and Monumentation

As GPS measurements have become more precise and are more frequently acquired, the issue of monumentation and site stability has become more important. Much attention is currently focused towards motions of the geodetic monument. These motions have been found by some researchers to be random-walk-like [e.g. *Johnson and Agnew, 1995]*, while others find no evidence for random walk behavior. An ideal GPS monument would move in response only to the tectonic motion of the Earth. However, location, ground, and the environment at ground surface can have dramtic impact on the long-term stability of a site.

*Johnson and* Agnew [1995] and *Johnson et al. [1996]* have reported evidence for power-law behavior in geodetic time-series using data from continuous GPS data from the SCIGN network in southern California, nearly-continuous two-color EDM measurements from Parkfield, and sea level data, The implication of this type of power-law noise is serious if the data are used to estimate low-frequency characterisitics of a time series such as the slope (deformation rate). Similarly *King et al.* [1'396] have used data from the permanent GPS array in northern California to evaluate the contribution of geological setting and monument design. Estimates of white noise are typically 2-3 mm in the horizontal and about 10 mm in the vertical. Estimates of monument noise, using the random-walk ($1/f^2$) model, are typically 2 to 5 $mm/yr^{1/2}$.

*Mao et al.* [1996] analyzed the three displacement components of six permanent GPS stations. The length of the GPS records is about 2.3 years. Their resulting power-spectral indices are close -0.5 for all three components. Davis *et al.* [1996] have estimated power spectra for the SWEPOS time series (3 years) of daily position estimates *[BIFROST project members, 1996]*. The power-law fit using spectral components from the lowest frequencies yielded spectral indices from -0.2 to -0.8. Thus, these time series show no evidence for random walk behavior. Mao *et al.* [1996] and *Davis et al. [1996]* found no tendency of *a* random-walk like behavior possibly because the records where not long enough to see a random walk component above the noise in the low portion of the signal. It is also quite possible that monument motion may depend critically on the monument design and the site locations. All stations in the BIFROST project are located on solid rock and utilize the same type of monument-pillars. These pillars are tied to a local control network, also situated on bedrock.

Nevertheless these investigations will continue and are most effectively addressed using continuous GPS measurements gathering data in a large variety of local conditions and GPS satellite configurations.

## *Implications for the IGS*

The IGS long-term contribution to the maintainance and densification of the global reference frame could be seriously affected by instable sites. The long-term stability of the reference frame and products associated with it, such as the orbits, are at issue here.

The IGS network consists of a large variety of monuments established on top of everything from solid bedrock to buildings. The extension and densification of the IGS network through the regional pilot project means inclusion of several stations from recent and probably more homogenous networks. One conclusion made from the work reviewed in this position paper is that the time-series may not be long enough yet.

There are design techniques which can be employed to mitigate this unwanted influence, most of which involve anchoring the monument to several points at depth and isolating the monument from surface material.

Suggestions: *(1) Attention should be paid to the* regional investigations *which have favorable and homogenous* conditions; (2) *Perform detailed spectral* analyses of *the IGS and other time series. Especially important is* to *examine the long* time *series available for* some *of the global sites. Monument and local stability problems could also manifest themselves as periodic periodic behavior, and be correlated with atmospheric* conditions and *precipitation. (3) Draw up more detailed recommendations for the monument ation at future IGS station.*

*It is important to realize that* many *studies still have to be performed, and that setting up* continuous *networks in many areas may be the only way to learn about* certain *effects such as "monument wander" and site stability.*

## Conclusion and Summary of Suggestions

Site-specific errors cannot be separated out when data from the global IGS sites are being used to determine orbits and reference frame. To be able to constrain the common mode of motion, sometimes in the submillimeter range, in a regional or local network a strong reference network is needed. The origin of the reference frame must be maintained with a high degree of robustness. In addition, orbits must be compatible with the reference frame. For this purpose the IGS sites need to be better examined. We especially found that the problems associated with the antenna/pillar system and the signal have to be addressed. The effect of the. antenna-signal related errors are constant from day-to-day but are biasing products like the orbit determination, station time series, and precipitable water vapor series. Any changes either at a station or in the GPS-data analysis strategy might change this bias and thereby effect the daily products and the reference frame. The other important issue that needs attention is the long-term stability of the sites and the monuments used in the IGS network. This is especially important bearing in mind that local and regional continuously operating GPS networks are now used to detect motion at the level of 1 mm/yr or less.

### Summary of suggestions

#### Antennas

The establishment of precise absolute calibrations of GPS antennas by means of chamber measurements and antenna pattern calculations is essential.

#### Antenna/pillar systems

Modeling of the scattering effect, or rather the complete phase response of the antenna system, including the pillar, is an important issue for future improvements of the GPS technique. One possibility to minimize these problems in the future would be to introduce specific recommendation on antenna/pillar system for new sites being established in the scientific GPS community. This system should, of course, be well- documented and phase-calibrated.

The problem in the existing IGS network is that unlike many of the local and regioal networks the antenna-pillar systems are quite different from station to station. The recommendation for those sites is that they should be carefully examined and calibrated. One alternative might be to draw up procedures for looking at the time series, behavior in elevation cut-off tests and the repeatability (day-to day) of multipath.

#### Radomes

The effects of radomes must be carefully investigated, including these effects on sites of IGS network. Recommendations for radome use should be developed. The changing of radomes should be carefully logged.

#### Precipitation

The effect of snow accumulation on the antenna/pillar system can introduce errors at the several cm-level. Methods to detect and model such errors need to be developed. Another option is of course to design antenna/pillar systems on which snow accumulation are less likely to take place.

#### Atmosphere

These effects could be significant at the mm-level or greater. Unfortunately, it is very difficult to isolate these effects from other elevation-angle-dependent effects (multipath, scattering, snow/ice, etc.). Small variations in the vertical component are also caused by these other error. We are thus not in the position of being able to correct for horizontal atmospheric gradients and loading errors optimally. At this point, theoretical studies are needed to quantify these effects, and to understand how we can best deal with these problems.

Local Stability and **Monumentation**

(1) Attention should be paid to the regional investigations which have favorable and homogeneous conditions; (2) Perform detailed spectral analyses of the IGS and other time series. Especially important is to examine the long time series available for some of the global sites. Monument and local stability problems could also manifest themselves as periodic periodic behavior, and be correlated with atmospheric conditions and precipitation. (3) Draw up more detailed recommendations for the monumentation at future IGS station.

It is important to realize that many studies still have to be performed, and that setting up continuous networks in many areas may be the only way to learn about certain effects such as "monument wander" and site stability.

## Recommendations

1) Develop detailed recommendations regarding the establishment of new IGS sites. Especially more information regarding antenna/pillar system effects, protective covers, and monumentation.

2) Develop procedures for assessing the quality of permanent sites. Such recommendations could include: RMS of long-term time series, power-spectra analysis of time-series, behavior in elevation cut-off tests, day-to-day repeatability of multipath, etc.

3) Compare IGS daily estimates of e.g., station coordinates and precipitable water vapour, to estimates obtained from other techniques.

4) Develop methods for electromagnetic calibration of IGS sites.

Most of the recommendations, not surprisingly, are similar to the objectives of the IAG Special Study Group 1.158 on GPS Antennas and Site Effects. Information about the IAG SSG is included in Appendix 1.

Acknowledgments Many people have contributed to this position paper through comments and suggestions. We would especially like to thank Jim Davis and Chuck Meertens for valuable contributions to the manuscript. This research was in part supported by (1) the EC Environment and Climate Research Programme, the Swedish Natural Research Council, and the Swedish National Space Board ; and (2) the National Aeronautics and Space Administration (USA) under contract to Jet Propulsion Laboratory, California Institute of Technology.

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'Appendix I

## International Association of Geodesy Special Study Group 1.158: GPS Antenna and Site Effects

### I- Terms of Reference

The improvement in precision obtained from GPS observations over recent years has revealed problems related to the local conditions at the GPS sites. In order to further improve high precision GPS positioning, orbit determination, and the estimates of atmospheric parameters, investigations of site dependent effects are required. The establishment of large numbers of permanent GPS stations on global, regional, and local scales has also raised concerns regarding the monuments used and the long- and short-term mechanical and electromagnetic stability of the sites. The goal of SSG 1.158 is to provide information and recommendations regarding the reduction of site dependent effects such as those related to GPS antennas, radomes, electromagnetic scattering, monuments and local stability, radio interference, and local atmospheric conditions. This goal will be achieved by providing a forum for discussions and for the exchange of ideas and literature. Interaction with the IGS community, regional and national GPS networks, and other study groups in Section I are essential to achieving the goals of the SSG.

### II- Objectives

The objectives of SSG 1.158 are to

(I) investigate the characteristics of different GPS antennas (mainly those used in high-precision applications) based on measurernents in anechoic chambers, field experiments, and numerical evaluation; study the effects of " antenna mixing;" design and evaluate new GPS antennas;

(II) study the influence of electromagnetic scattering (including multipath) and provide information on how to minimize these effects;

(III) investigate and formulate recommendations regarding establishment of new GPS sites, including the design and construction of pillars (monuments) and the monitoring of their long-term stability; evaluate radomes used to protect permanently installed antennas;

(IV) study and minimize the influence of snow, rain, and local atmospheric conditions on the final estimates;

(V) provide information and recommendations on how to eliminate (or minimize) the effects of radio interference.

The outcome of these activities will be *summarized* in a final report which contains information regarding site dependent effects and how to minimize them, recommendations (wherever possible) of appropriate solutions for the establishment of new GPS sites, and proposed modifications to GPS processing standards.

List of **Members** Jan Johansson (President), James Campbell, Thomas Clark, James Davis, Charley Dunn, Alain Geiger, Kenneth Jaldehag, Hannu Koivula, Richard Langley, Kristine Larson, Gerry Mader, Chuck Meertens, Peter Morgan, Antonio Rius, Markus Rothacher, Bruce Schupler, James Tranquilly, Danny Van Loon, Luca Vittuari, Rene Warnant, Geoffrey Blewitt, Beat Burki, Ulf Lindqwister, Sammy Musyoka, Chris Rizos, Wolgang Schlueter, Hiromichi Tsuji, Arthur Niell, Tom Herring

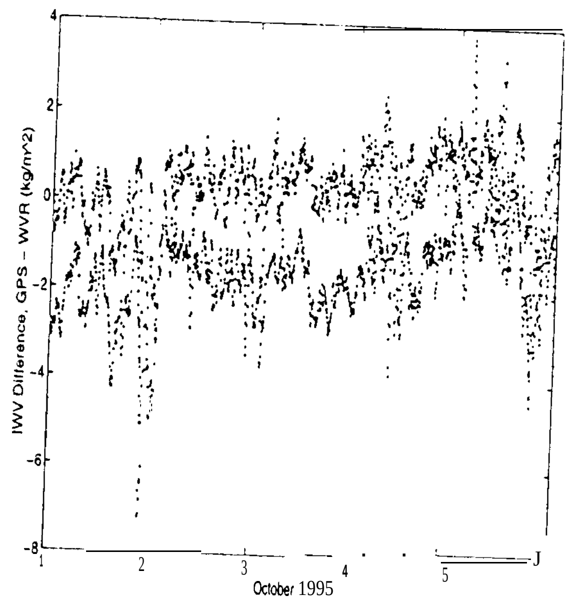


Figure 1. Difference between the GPS estimated IWV, and the WVR data for six days in the beginning of October 1995. The two different solutions are carried out with 10, and 15 degrees elevation cutoff angle respectively shown as the black, and the light gray curves. We can see that the two solutions show a similar pattern, the 10 degree curve however around zero, and the 15 degree around 2 $kg/m^2$.

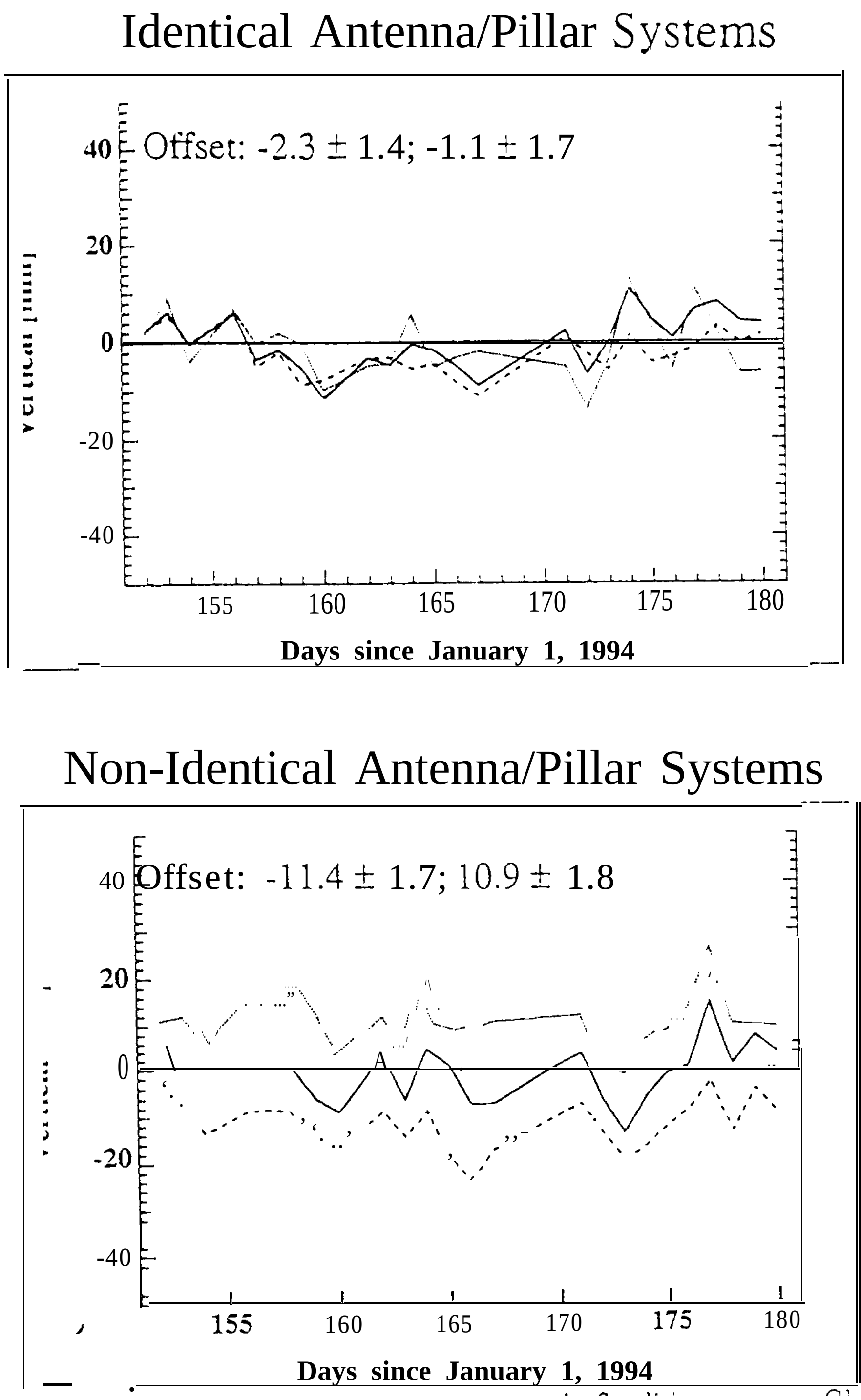


Figure 2. Daily estimates of the vertical component of baselines in the Swedish permanent GPS network between stations with; (top) identical antenna/pillar systems; and (bottom) non-identical antenna/pillar systems for three different elevation cutoff angles, namely 10° (dashed lines), 15° (solid lines), and 20° (dotted lines).

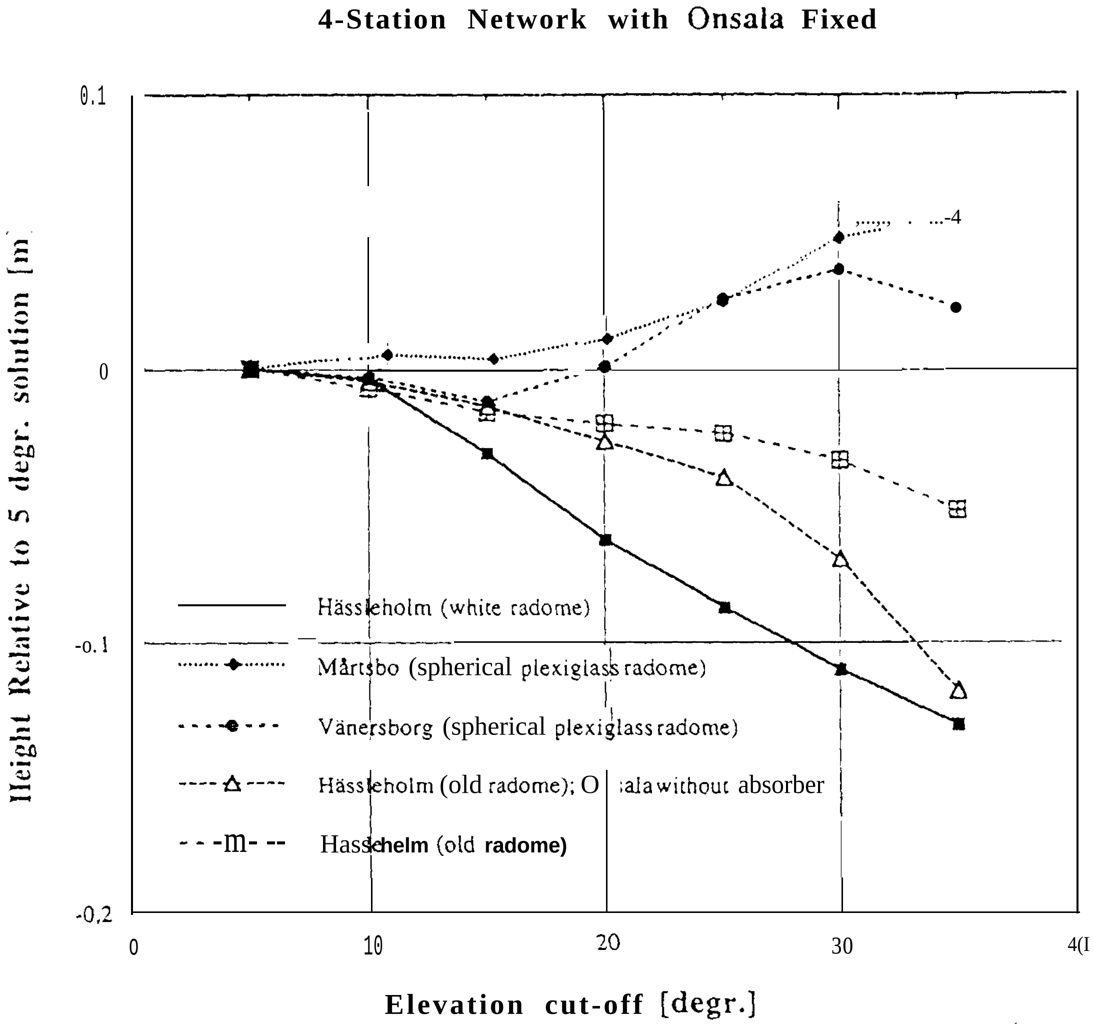


Figure 3. Elevation cutoff angle test using a four station network in Sweden. The Onsala IGS station was held fixed in the solution. The Onsala site is equipped with cone-shaped radome of the old Delft type. Stations Mårtsbo and Vänersborg were using a new hemispheric plexi-glas cover, and Hässleholm was equipped with a plastic radome with a steep concical shape. Included are also an earlier study when the Hässleholm site was equipped with a conical radome of the same type as Onsala.

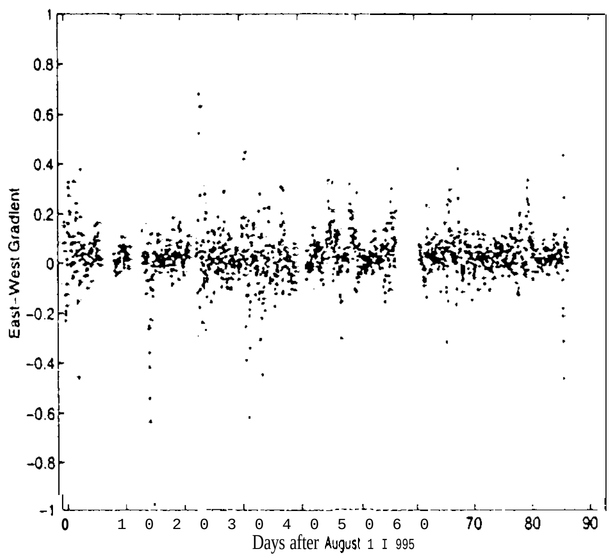


Figure 4. East-west gradients at Onsala with the formal one-sigma error bars estimated from WVR data.